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# 100G Flexible IM-DD 850 nm VCSEL Transceiver with Fractional Bit Rate Using Eight-Dimensional PAM

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**Abstract** *We demonstrate a novel optical transceiver scheme with a net flexible bit rate up to 100Gbit/s with 5 Gbit/s granularity, using an eight-dimensional modulation format family, and investigate its performance on capacity, reach, and power tolerance.*

## Introduction

Optimizing the utilization of hardware resources and achieving a target transmission performance is a fundamental objective in the design of intensity-modulated direct-detection (IM-DD) transceivers using pulse-amplitude modulation (PAM). As illustration, for a given link configuration, using PAM-4 may underuse available output power; whereas stepping up to PAM-8 can be hindered by insufficient power budget. A solution to this gap is found in the use of multi-dimensional (MD) modulation formats<sup>1,2</sup>, carrying a fractional number of bits per symbol (bit/sym). Furthermore, such MD formats enable bit-rate flexible transmission. The concept of using four-dimensional (4D) formats in a rate flexible transceiver<sup>3</sup> and a multi-rate IM-DD transceiver using 4D formats<sup>4</sup> have been proposed. Recently, 8D modulation format has been reported for coherent detection<sup>5,6</sup> and IM-DD systems<sup>7</sup>.

In this paper, we propose, design and experimentally investigate a flexible IM-DD transceiver with software-controlled bit rate, using a newly designed 8D format family, which has a spectrum efficiency granularity of 0.125 bit/sym. Such flexible transceiver effectively utilizes bandwidth and power budget resources and benefits from the hardware simplicity of PAM- $m$  modulators. By using a fractional number of bit/sym, we demonstrate a net 100Gbit/s transmission over 200 m OM4 MMF and gross 100Gbit/s over 1 km SSMF, where otherwise both PAM-4 and PAM-8 fail.

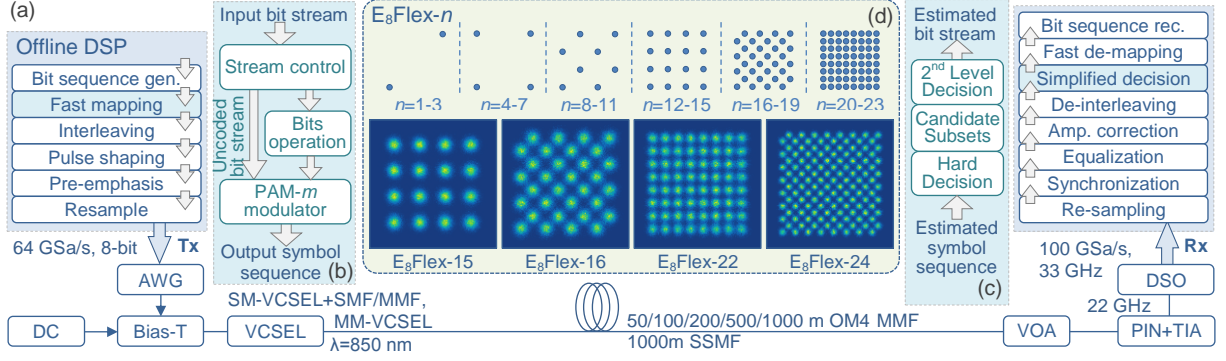
## E<sub>8</sub>Flex- $n$ and bitrate flexible transceiver

For realizing the novel software-controlled rate flexibility, we design an 8D format family, i.e. E<sub>8</sub>Flex- $n$ , together with its fast (de)mapping algorithm and simplified decision scheme. Similar to BB8 format<sup>7</sup>, E<sub>8</sub>Flex- $n$  is based on an E<sub>8</sub> lattice grid and uses eight temporally consecutive symbols to form an 8D super-symbol (s-sym). Each s-sym carries  $n$  bits,

namely  $n/8$  bits per conventional symbol, giving a 0.125 bit/sym granularity. The BER sensitivity increases when reducing the constellation scale, where the minimum Euclidean distance is enlarged or the format set gets sparser. Despite the complex 8D geometry, each transmitted symbol set is equivalent to a conventional PAM symbol with evenly distributed levels. E<sub>8</sub>Flex- $n$  is derived from BB8 and covers a family of 8D formats. For example, E<sub>8</sub>Flex-15 is equivalent to the earlier reported 8D formats<sup>5</sup> and E8Flex-16 is equivalent to BB8<sup>7</sup>. Borrowing the methods of the latter, we extend the fast (de)mapping algorithm to all E<sub>8</sub>Flex- $n$  from  $n=1$  to an arbitrary number, within a uniform modulation framework. The bit mapping of this modulation is further modified to enable the swift and smooth scale alteration. E<sub>8</sub>Flex- $n$  modulation is bit-stream based without using the look-up table containing the symbol alphabets. Only bit-level operations are required before the PAM- $m$  modulator. The bit stream volume fed to the modulator is simply controlled by the control bits. During the decision phase, we first apply hard decision on each PAM symbol and make final decision among 2, 4, 8 or 16 candidate 8D points, according to the format scale ( $n$ ). The proposed scheme uses a fixed baud rate and shifts the bit rate only by using the formats of different scales.

## Experimental setup

For comparison purposes, in the experimental setup (Fig. 1) we use different types of 850 nm vertical-cavity surface-emitting lasers (VCSELs) – a multi-mode (MM) VCSEL, and two single-mode (SM) VCSELs coupled with multi-mode fiber (MMF) and single-mode fiber (SMF) pigtails, respectively. The –3 dB bandwidth of the MM-VCSEL and SM-VCSELs reaches 18 GHz and 20 GHz respectively, and the optical output power levels reach 4 dBm (MM-VCSEL), 0.5 dBm (MMF-coupled SM-VCSEL) and –1.7 dBm (SMF-coupled SM-VCSEL).



**Fig. 1:** (a) Scheme of the experimental setup; (b) Scheme of the fast mapping; (c) Scheme of the simplified decision; (d) 2D projections of E8Flex-n constellations.

After transmission through the fiber links of different lengths, the optical signal is detected by a calibrated photoreceiver module with co-packaged transimpedance amplifier (TIA). At the transmitter, for each measured trace, 30 Mbit input streams were generated randomly for avoiding the pattern dependent effects and mapped with the fast E8Flex mapper. After interleaving, the symbol sequences were resampled to the desired baud rate and shaped into raised cosine/root raised cosine pulses. The spectra of output sequences were pre-emphasized, for compensating the electrical spectral roll-off of the transmitter. During the offline digital signal processing (DSP) at the receiver side, the electrical signal was resampled into two times of the baud rate, and after sequence synchronization it was equalized by a  $T/2$  fractional FFE together with an amplitude correction. After de-interleaving, the output bit streams were obtained by the E8Flex de-mapper.

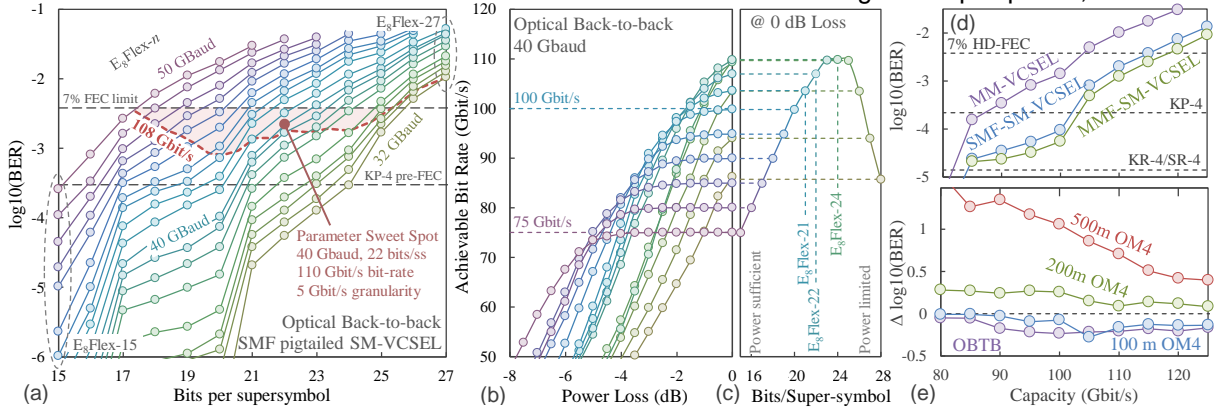
## Experimental results

**Bandwidth requirement:** Fig. 2(a) shows the optical back-to-back (OBTB) performance for different numbers of bit/sym with various baud rates. The red dot curve indicates the gross 108G threshold. The parameters chosen from the shadowed area enable the net 100G

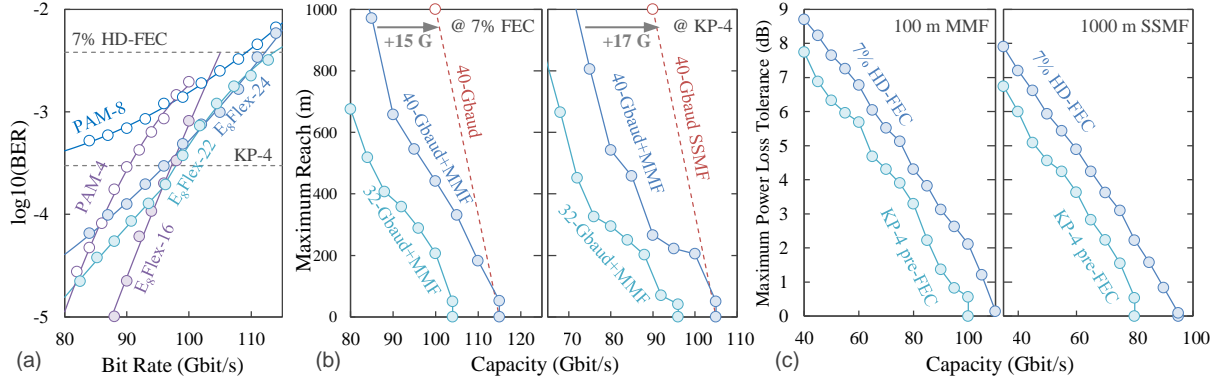
transmission and beyond. It follows that 22 bit/s-sym in 40 Gbaud systems is a fair choice, which gives a trade-off between bit rate and system bandwidth, providing a gross rate of 110 Gbit/s. Thus, in the later tests, we use 40 Gbaud for the system investigation and 32 Gbaud as a reference, which correspond to 5 Gbit/s and 4 Gbit/s granularity respectively.

**Capacity:** The OBTB performance of SM-VCSEL shows a transmission potential up to 110 Gbit/s within the power budget of our experimental setup, see Fig. 2(b). As Fig. 2(c) shows, achievable bit rate starts to saturate at 23 bit/s-sym due to limited power. It implies that E8Flex-22 has a near optimal utilization of the laser output power and guarantees the net 100G transmission. Another interesting point is E8Flex-21, which has a lower bit rate but simplest decision procedure among E8Flex-16 to E8Flex-23.

**VCSEL comparison:** Fig. 2(d) shows the system performance in OBTB mode with three different types of VCSELs, demonstrating better behavior of SM-VCSELs compared to MM-VCSEL. Fig. 2(e) provides comparison of SMF- and MMF-pigtailed SM-VCSELs for different transmission lengths, showing that MMF-pigtailed SM-VCSEL provides slightly better BER performance in case of OBTB and 100m MMF link because of higher output power, but SMF-



**Fig. 2:** (a) BER performance vs. the number of bits per super-symbol for different symbol rate values; (b,c) Achievable bit rate for different numbers of bits per super-symbol; (d) BER performance vs. channel capacity for different types of VCSEL modules in OBTB mode; (e) BER difference between MMF- and SMF-pigtailed SM-VCSELs vs. channel capacity for different MMF links at 40 Gbaud symbol rate.



**Fig. 3:** (a) BER performance vs. bit rate in OBTB mode for conventional PAM and E8Flex formats. (b) Maximum reach vs. channel capacity for 7% overhead hard-decision FEC BER threshold (left), and KP4 FEC BER threshold (right). (c) Maximum power loss tolerance vs. channel capacity for 100 m OM4 MMF link (left) and 1 km SSMF link (right).

pigtailed SM-VCSEL significantly outperforms MMF-pigtailed one at the fiber lengths from 200 m. Meanwhile, SMF-pigtailed SM-VCSEL provides a possibility of transmission over standard ITU-T G.652 compliant SMF (SSMF). Thus, for further investigation on the features of the proposed transceiver scheme the SMF-pigtailed SM-VCSEL is used.

**Comparing with PAM signals:** we observe from Fig. 3(a) that using both PAM-4 and PAM-8 at any symbol rate 100G net transmission is not achievable, but it can be achieved by 40Gbaud E<sub>8</sub>Flex-*n*, using fractional numbers of bit/sym. Noteworthy, E<sub>8</sub>Flex-16 and E<sub>8</sub>Flex-24 formats, which have the same bit/sym as to PAM-4 and PAM-8 respectively, outperform their conventional PAM counterparts due to the optimized geometrical features<sup>7</sup>.

**Reach:** Fig. 3(b) shows the maximum reach vs. the bit rate under the BER limits of different FEC schemes. The maximum reach values are estimated by fitting the results of transmission over 50, 100, 200, 500 m and 1 km MMF links. It is noteworthy that SSMF provides a gross 100G bit rate over 1 km link and outperforms the 500 m MMF link by the capacity×distance product.

**Power penalty** is estimated in Fig. 3(c) for different data rates over 100 m MMF and 1 km SSMF links respectively. The general linearity of power penalty (SNR) vs. capacity (bit/s-sym) curves offers convenience in designing the capacity aware transceivers.

## Conclusions

We propose a new flexible and fast 8D modulation family and experimentally verify its performance in 850nm SM-VCSEL based optical transceiver scheme. The proven merits of E<sub>8</sub>Flex-*n* include: (1) a smooth and swift software defined transition between bit rates without altering the hardware configuration or resampling; (2) higher sensitivity in the low noise regime; (3) optimized usage of hardware resources; (4) easy (de)mapping and

(de)modulation procedures, utilizing PAM-*m* signal as a basis; (5) intrinsic compatibility with the future industry standard of multi-lane optical interconnects, e.g. octal small-factor pluggable (OSFP). A single format in E<sub>8</sub>Flex-*n* family can serve as a format for a specific fixed bit rate system, offering an optimum between the bandwidth utilization and system performance. Besides the IM-DD scenario, E<sub>8</sub>Flex-*n* can be also considered as a candidate for format and bit rate flexible transmission in coherent detection systems, too.

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